

ELECTRON-ELECTRON INTERACTION IN CARBON NANOSTRUCTURES

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Abstract. The electron-electron interaction in carbon nanostructures was studied. A new method which allows to determine the electron-electron interaction constant λ_c from the analysis of quantum correction to the magnetic susceptibility and the magnetoresistance was developed. Three types of carbon materials: arc-produced multiwalled carbon nanotubes (arc-MWNTs), CVD-produced catalytic multiwalled carbon nanotubes (c-MWNTs) and pyrolytic carbon were used for investigation. We found that $\lambda_c=0.2$ for arc-MWNTs (before and after bromination treatment); $\lambda_c = 0.1$ for pyrolytic graphite; $\lambda_c > 0$ for c-MWNTs. We conclude that the curvature of graphene layers in carbon nanostructures leads to the increase of the electron-electron interaction constant λ_c .

Key words: Electron-electron interaction; Nanostructures; Electronic transport; Galvanomagnetic effects; Quantum localization

1. Introduction

The carbon nanostructures are formed of graphene layers which always have some curvature. As a result, these materials are characterized by new properties which are not present in graphite consists of plane graphene layers. The curvature of the graphene layers influences the electron-electron interaction in these systems. The most interesting consequence of the graphene layers curvature is the existence of a superconducting state in bundles of single-walled carbon nanotubes with diameters of 10 Å at temperatures below $T_c \approx 1$ K (Kociak et al., 2001) as well as the onset of superconductivity at $T_c \approx 16$ K in nanotubes with diameters of 4 Å (Tang et al., 2003) and at $T_c \approx 12$ K in entirely end-bonded multiwalled carbon nanotubes (Takesue et al., 2006). In contrast, in graphite no superconducting state is observed. Y. Kopelevich *et al.* (Kopelevich et al., 2000) proposed that superconductivity may appear in ideal graphite and that the absence of superconductivity



in real samples is related to the defects always present in graphite. According to theoretical predictions of (Gonzalez et al., 2001) topological disorder can lead to an increase in the density of states at the Fermi surface and to an instability of an electronic subsystem. These changes in the electronic system could lead to a superconducting state. However, such topological disorder leads to a curvature of initially flat graphene layers. We assume, therefore, that in carbon nanostructures the superconducting state is related to the curvature of graphene layers. The curvature of surfaces is always present in the crystal structure of nanocrystallites. As a result, in such structures the electron-electron interaction should be modified. This paper is devoted to the analysis of experimental data which allows to determine the electron-electron interaction constant λ_c in carbon nanostructures formed by curved graphene layers.

2. Experimental methods

The method of our investigation of the electron-electron interaction constant is based on the joint analysis of quantum corrections to the electrical conductance, magnetoconductance and magnetic susceptibility. For all nanostructures formed by graphene layers the presence of structural defects leads to the diffusive motion of charge carriers. As a result, at low temperatures, quantum corrections to the electronic kinetic and thermodynamic quantities are observed. For the one-particle processes (weak localization - WL (Kawabata, 1980; Lee and Ramakrishnan, 1985)) these corrections arise from an interference of electron wave functions propagating along closed trajectories in opposite directions, provided the lengths l of these trajectories are less than the phase coherence lengths $L_\varphi(T) = (D\tau_\varphi)^{1/2}$ (D is the diffusion constant and $\tau_\varphi = T^{-p}$ is the characteristic time for the loss of phase coherence with an exponent $p = 1 \div 2$). As a result, the total conductance of the system is decreased. $L_\varphi(T)$ increases with decreasing temperature which, in turn, leads to the decrease of the total conductance. In a magnetic field there is an additional contribution to the electronic phase, which has an opposite sign for opposite directions of propagation along the closed trajectory. As a result, the phase coherence length is suppressed: $L_B = (\hbar c / 2eB)^{1/2} < L_\varphi$. Here $L_B = (\hbar c / 2eB)^{1/2}$ the magnetic length, c is the light velocity, e - the electron charge, B - the magnetic field. This leads to negative magnetoresistance, i.e. to an increase of conductance in a magnetic field. Quantum corrections also arise from the interaction between electrons (interaction effects - IE (Al'tshuler et al., 1983)). These corrections arise due to the phase memory between two consecutive events of electron-electron scattering. If the second scattering event happens at a distance shorter than the coherence length, $L_{IE} = (D\hbar/k_B T)^{1/2}$, from the first one (L_{IE} being the length on which the information about the changes of the electronic phases due to the first scattering event is not yet lost), the second scattering will depend on the first one. As a result the effective density of states on the Fermi surface ν_F is

renormalized. Interaction effects contribute not only to electrical conductance, but also to thermodynamic quantities depending on v_F - magnetic susceptibility χ and heat capacity C .

3. Results and discussion

3.1. ARC-PRODUCED MULTIWALLED CARBON NANOTUBES

A characteristic peculiarity of our arc-MWNTs (Okotrub et al., 2001; Romanenko et al., PSS, 2002) is the preferential orientation of the bundles of nanotubes in the plane perpendicular to the electrical arc axis. The volume samples of our arc-MWNTs show anisotropy in their electrical conductivity $\sigma_{||}/\sigma_{\perp} \approx 100$ (Okotrub et al., 2001; Romanenko et al., PSS, 2002). $\sigma_{||}$ is the electrical conductivity in the plane of preferential orientation of the bundles of nanotubes, σ_{\perp} is the conductance perpendicular to this plane. The average diameter of individual nanotubes is $d_{MWNT} \approx 140$ Å. According to the electron paramagnetic resonance data, the concentration of paramagnetic impurities in our samples is less than 10^{-6} . This excludes a substantial contribution of the impurities to the susceptibility. The MWNTs brominated at room temperature in bromine vapour (Romanenko et al., PSS, 2002) have a composition of $CBr_{0.06}$. The addition of bromine leads to an increase of the conductivity, which can be attributed to an increase in the concentration of hole current carriers.

According to experimental and theoretical data, the basic contribution in χ of quasi-two-dimensional graphite (QTDG), including MWNTs, gives orbital magnetic susceptibility χ_{or} connected with extrinsic carriers (EC). Figures 1(a) and 2(a) present the magnetic susceptibility χ of arc-MWNTs samples before bromination and after bromination as a function of temperature respectively. Available models well reproduce the temperature dependence of magnetics susceptibility for MWNTs only at $T > 50$ K. In the low-temperature region the experimental data deviate from the theoretical ones. According to theoretical consideration the magnetic susceptibility χ of quasi-two-dimensional graphite (QTDG) is generally contributed by the component χ_D (Kotosonov et al., 1997)

$$\chi_{or}(T) = -\frac{5.45 \times 10^{-3} \gamma_0^2}{(T + \delta)[2 + \exp(\eta) + \exp(-\eta)]}, \quad (1)$$

where γ_0 is the band parameter for two-dimensional case, δ is the additional temperature formally taking into account "smearing" the density of states due to electron nonthermal scattering by structure defects, $\eta = E_F/k_B(T + \delta)$ represents reduced Fermi level (E_F), k_B is the Boltzmann constant. Using an electrical neutrality equation in the 2D graphite model (Kotosonov et al., 1997) η can be derived by $\eta = \text{sgn}(\eta_0)[0.006\eta_0^4 - 0.0958\eta_0^3 + 0.532\eta_0^2 - 0.08\eta_0]$ with an accuracy no less than 1%. The η_0 is determined by $\eta_0 = T_0/(T + \delta)$, where T_0 being degeneracy

temperature of extrinsic carriers (EC) depends on its concentration n_0 only. The value of δ can be estimated independently as $\delta = \hbar/\pi k_B \tau_0$, where \hbar is the Planck constant, τ_0 is a relaxation time of the carrier nonthermally scattered by defects. Generally, the number of EC in QTDG is equal to that of scattering centers and δ depends only on T_0 , i.e. $\delta = T_0/r$, where r is determined by scattering efficiency. These parameters were chosen to give the best fit of the experimental data.

According to theoretical calculations (Al'tshuler et al., 1983), the correction $\Delta\chi_{or}$ to the orbital susceptibility χ_{or} in the Cooper channel dominates the quantum correction to the magnetic susceptibility $\chi(T, B)$ in magnetic fields smaller than $B_c = (\pi k_B T / g \mu_B)$ ($B_c = 9.8$ T at 4.2 K). These corrections are determined by the value and the sign of the electron-electron interaction constant λ_c and are proportional to the diamagnetic susceptibility of electrons χ_{or} . In graphite and MWNTs the diamagnetic susceptibility is greater than in any other diamagnetic material (excluding the superconductors), and the correction to χ_{or} should also be large. $\Delta\chi(T)_{or} = \chi(T)_{or}^{exp} - \chi(T)_{or}$ was found by (Lee and Ramakrishnan, 1985; Al'tshuler et al., 1983):

$$\frac{\Delta\chi_{or}(T)}{\chi_{or}(T)} = -\frac{\frac{4}{3}(\frac{l_{el}}{h})\ln[\ln(\frac{T_c}{T})]}{\ln(\frac{k_B T_c \tau_{el}}{h})}, (d = 2), \quad (2)$$

$$\frac{\Delta\chi_{or}(T)}{\chi_{or}(T)} = -\frac{2(\frac{\pi}{6})\xi(\frac{1}{2})(\frac{k_B T \tau_{el}}{h})^{1/2}}{\ln(\frac{T_c}{T})}, (d = 3), \quad (3)$$

where $\chi(T)_{or}^{exp}$ are the experimental data, $\chi(T)_{or}$ is the result of an approximation of the experimental data in an interval of temperatures 50 - 400 K by the theoretically predicted dependence (1) for quasi-two-dimensional graphite (Kotosonov et al., 1997); value of $\xi(\frac{1}{2}) \sim 1$, l_{el} is the electron mean free path; τ_{el} represents the elastic relaxation time which is about 10^{-13} sec for MWNT (Baxendale et al., 1997); h is the thickness of graphene layers packet; d denotes the dimensionality of the system; $T_c = \theta_D \exp(\lambda_c^{-1})$, where θ_D is the Debye temperature, λ_c is the constant which describes the electron-electron interaction in the Cooper channel ($\lambda_c > 0$ in a case of electron repulsion). The dependence in Eq. (2) is determined by $\ln[\ln(\frac{T_c}{T})]$ term because, at low temperatures, in the disordered systems, τ_{el} is temperature independent while all other terms are constants. The dependence in Eq. (3) is governed by $T^{1/2}$ term as $T_c \gg T$ and, therefore, $\ln(\frac{T_c}{T})$ can be considered as a constant relative to $T^{1/2}$. The temperature dependence of the magnetic susceptibility $\chi(T)$ is shown in figure 1 for arc-MWNTs before bromination, in figure 2 for arc-MWNTs after bromination, and in figure 3 for crystal graphite. Below 50 K the deviation of experimental data from the theoretical curve is observed (Romanenko et al., SSC, 2002; Romanenko et al., 2003). The additional contribution to $\chi(T)$ is presented in Fig. 1(b), 2(b), 3(b); and Fig. 1(c), 2(c), 3(c) as a function of $\ln[\ln(\frac{T_c}{T})]$ and $T^{1/2}$ respectively. The

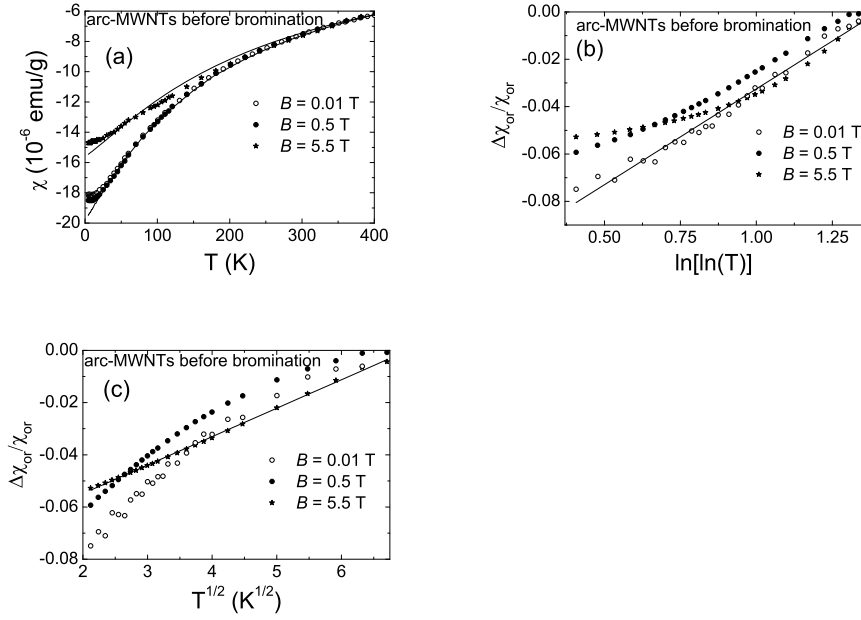


Figure 1. The temperature dependence of magnetic susceptibility $\chi(T)$ (a) and $\Delta\chi_{or}(T)/\chi_{or}(T) = [\chi(T) - \chi_{or}(T)]/\chi_{or}(T)$ [(b) and (c)] for arc-produced MWNTs sample before bromination. The solid lines are fits: for (a) by Eq. (1) in interval 50 - 400 K with parameters; for curve (○), $\gamma_0 = 1.6$ eV, $T_0 = 215$ K, $\delta = 159$ K; for (●), $\gamma_0 = 1.6$ eV, $T_0 = 215$ K, $\delta = 159$ K; for (★), $\gamma_0 = 1.7$ eV, $T_0 = 327$ K, $\delta = 210$ K; by Eq. (2) and Eq. (3) for (b) and (c) respectively in interval 4.5 - 45 K with parameters $T_c = 10000$ K, $l_{el}/a = 0.15$.

$\Delta\chi_{or}(T)/\chi_{or}(T)$ clearly shows the dependence given by Eq. (2) at low magnetic field and one given by Eq. (3) at high magnetic field, while at $B = 0.5$ T the temperature dependence of $\Delta\chi_{or}(T)/\chi_{or}(T)$ differs from those two limits. As seen from Fig. 1, at all magnetic fields applied to the arc-MWNTs before bromination, the absolute value of $\Delta\chi_{or}(T)/\chi_{or}(T)$ increases with decreasing temperature as has been predicted for IE in the systems characterized by electron-electron repulsion (Lee and Ramakrishnan, 1985; Al'tshuler et al., 1983). Hence, at $B = 5.5$ T a crossover from the two-dimensional IE correction to the three-dimensional one takes place. At lower magnetic field the interaction length $L_{IE}(T)$ is much shorter than the magnetic length L_B , which in turn becomes dominant at high field. An estimation of the characteristic lengths gives respectively the value of $L_{IE}(4.2K) = 130$ Å (taking into account that the diffusion constant $D = 1$ cm²/s (Baxendale et al., 1997)) and the value of $L_B = 100$ Å at $B = 5.5$ T.

A similar dependence of $\Delta\chi_{or}(T)/\chi_{or}(T)$ was observed for arc-MWNTs after bromination (Fig. 2).

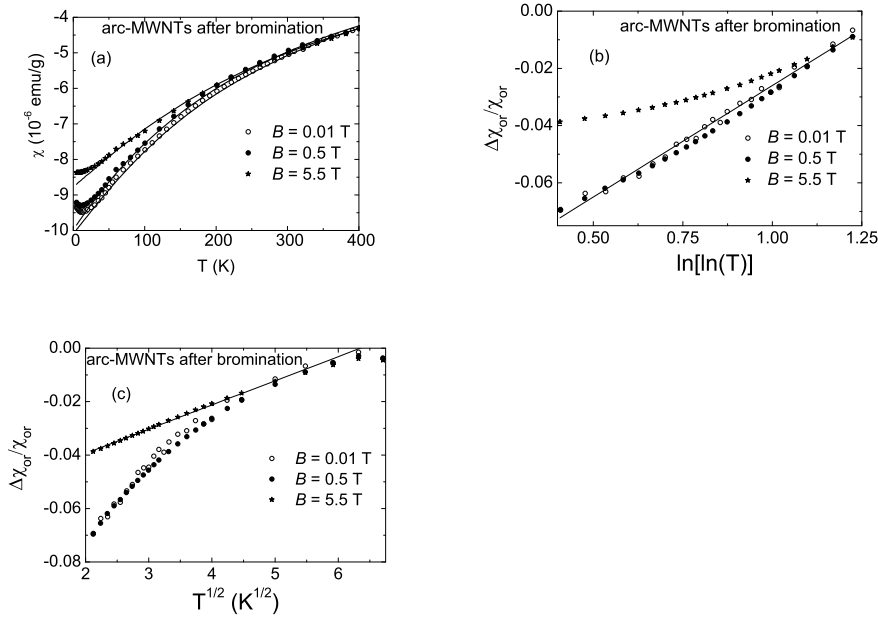


Figure 2. The temperature dependence of magnetic susceptibility $\chi(T)$ (a) and $\Delta\chi_{or}(T)/\chi_{or}(T) = [\chi(T) - \chi_{or}(T)]/\chi_{or}(T)$ [(b) and (c)] for arc-produced MWNTs sample after bromination. The solid lines are fits: for (a) by Eq. (1) in interval 50 - 400 K with parameters; for curve (○), $\gamma_0 = 1.4$ eV, $T_0 = 340$ K, $\delta = 252$ K; for (●), $\gamma_0 = 1.4$ eV, $T_0 = 300$ K, $\delta = 273$ K; for (★), $\gamma_0 = 1.5$ eV, $T_0 = 435$ K, $\delta = 325$ K; by Eq. (2) and Eq. (3) for (b) and (c) respectively in interval 4.5 - 45 K with parameters $T_c = 10000$ K, $l_{el}/a = 0.15$.

The dependence of $\Delta\chi_{or}(T)/\chi_{or}(T)$ we investigated for crystals of graphite (Fig. 3). However, only the three-dimensional dependence $\Delta\chi_{or}(T)/\chi_{or}(T) \approx T^{1/2}$ was found for graphite.

Approximation of the abnormal part of the magnetic susceptibility by theoretically predicted functions has revealed three features:

I. A crossover from the two-dimensional quantum corrections to $\chi(T)$ in fields $B = 0.01$ T to the three-dimensional quantum corrections in field $B = 5.5$ T is observed as up to bromination of arc-MWNTs, so after bromination of its when the magnetic field increases. For graphite, in all fields, the three-dimensional corrections to $\chi(T)$ are observed. This is related to the fact that magnetic length $L_B = 77$ Å in fields of $B = 5.5$ T becomes comparable to the thickness of the graphene layers h_{MWNT} which form the MWNT. On the other hand, in fields of $B = 0.01$ T, $L_B = 1800$ Å is much longer than h_{MWNT} but it is shorter than the length of a tube l_{MWNT} ($l_{MWNT} \approx 1\mu$) and is comparable to the circumference of a nanotube. In graphite, the thickness of a package of the graphene layers is always

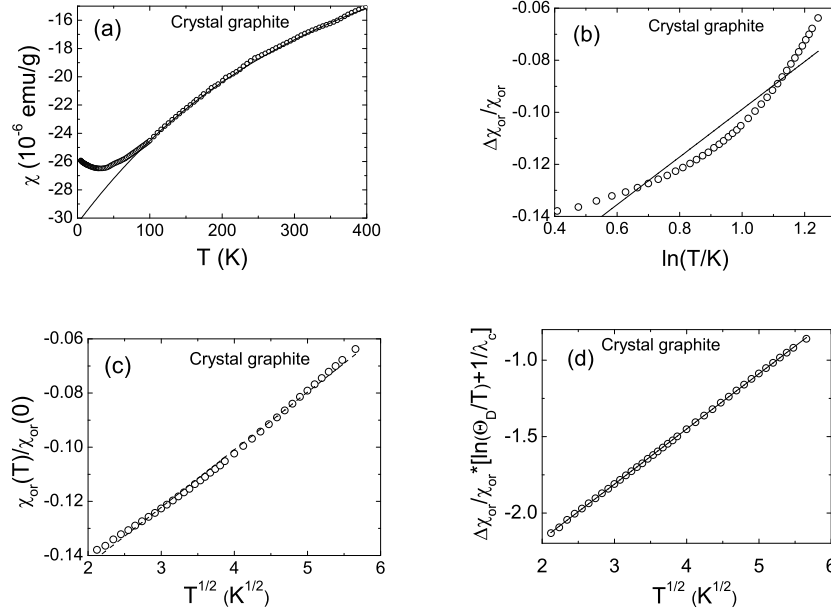


Figure 3. Temperature dependences of a magnetic susceptibility $\chi(T)$ for graphite measured in a magnetic field = 0.01 T. Continuous lines show: the regular parts $\chi(T)$ (a); two-dimensional quantum corrections to $\chi(T)$ (b); three-dimensional quantum corrections to $\chi(T)$ (c), (d). The solid lines are fits for (d) by Eq. (3) in interval 4.5 - 45 K with parameters $\theta_D = 1000$ K, $\lambda_c = 0.1$.

macroscopic and it exceeds all other characteristic lengths.

II. The bromination of arc-MWNTs has led to an increase of their conductance by one order of magnitude (from $500 \Omega^{-1}\text{cm}^{-1}$ in arc-MWNTs before bromination up to $5000 \Omega^{-1}\text{cm}^{-1}$ after bromination). However, the relative correction to the magnetic susceptibility $\Delta\chi(T)_{or}/\chi(T)_{or}$ which determines the value of λ_c , remained constant. Thus, the bromination does not change the electron-electron interaction constant λ_c in the arc-produced multiwalled carbon nanotubes.

III. The constant of electron-electron interaction λ_c for arc-MWNTs before and after bromination has the magnitude about 0.2 (Romanenko et al., SSC, 2002) which is greater than that of graphite $\lambda_c \approx 0.1$ (Romanenko et al., 2003), i.e. the curvature of the graphene layers in MWNTs leads to the increase of λ_c .

The temperature dependence of the electrical conductivity $\sigma(T)$ of arc-MWNTs indicates the presence of quantum corrections also (Fig. 4(a) and Fig. 5(a)). At low temperatures, the temperature dependence of these quantum corrections is characteristic for the two-dimensional case (Fig. 4(b) and Fig. 5(b)):

$$\Delta\sigma(T) = \Delta\sigma_{WL}(T) + \Delta\sigma_{IE}(T). \quad (4)$$

Here $\Delta\sigma_{WL}(T) \approx \ln(L_\varphi/l_{el})$ is the correction associated with the quantum interference of noninteracting electrons in two-dimensional systems (WL) (Lee and Ramakrishnan, 1985; Kawabata, 1980) while $\Delta\sigma_{IE}(T) \approx \ln(L_{IE}/l_{el})$ is the correction associated with the quantum interference of interacting electrons (IE) in such systems (Lee and Ramakrishnan, 1985; Al'tshuler et al., 1983). The contribution of quantum corrections to the electrical conductivity should be accompanied by corrections to magnetoconductivity $\Delta\sigma(B) = 1/\rho(B)$ in low magnetic fields (Kawabata, 1980; Al'tshuler et al., 1981):

$$\Delta\sigma(B) = \Delta\sigma_{WL}(B) + \Delta\sigma_{IE}(B). \quad (5)$$

Here $\Delta\sigma_{WL}(B)$ is the quantum correction to magnetoconductance for noninteracting electrons; $\Delta\sigma_{IE}(B)$ - the quantum correction to the magnetoconductance for interacting electrons. Both corrections have the logarithmic asymptotic in high magnetic fields ($\Delta\sigma_{WL}(B) \approx \ln(L_\varphi/L_B)$; $\Delta\sigma_{IE}(B) \approx \ln(L_{IE}/L_B)$ at L_φ/L_B ; $L_{IE}/L_B \gg 1$), and the quadratic asymptotic in low magnetic fields ($\Delta\sigma_{WL}(B) \approx B^2$; $\Delta\sigma_{IE}(B) \approx B^2$ when L_φ/L_B ; $L_{IE}/L_B \ll 1$). The quantum corrections to magnetoconductance become essential in low magnetic fields when the magnetic length is $L_B < L_\varphi$. In this case the phase of an electron is lost at distances $\approx L_B$, and quantum corrections to conductance are partially suppressed. This leads to positive magnetoconductance (negative magnetoresistance).

It is difficult to divide the contribution of IE in the Cooper channel (which is determined by the amplitude and sign of λ_c), WL and IE in the diffusion channel. Field dependences of magnetoresistance (Fig. 4(c)) in all intervals of the measured fields (0 - 1 T) show negative magnetoresistance, related to WL. Similar dependences are observed in graphite (Fig. 4(d)). All three mechanisms give quantum corrections to temperature dependence of conductance $\sigma(T)$. In order to observe the contribution of IE in the superconducting channel it is necessary to exclude the contribution of WL. We achieved this in catalytic carbon multiwalled nanotubes which were synthesized by a technology which prevents the formation of other phases of carbon.

3.2. CATALYTIC MULTIWALLED CARBON NANOTUBES

There are always paramagnetic impurities present in c-MWNTs because of the ferromagnetic metals used as catalytic agents. It is not possible to use the magnetic susceptibility in order to obtain information on $\Delta\chi_{or}(T)$ of c-MWNT, because the contribution of paramagnetic impurities dominates at low temperatures. We carried out an analysis of the conductivity data for which the contribution of paramagnetic impurities is negligible. In figure 5(c) the dependence of the relative magnetoconductivity $\rho(B)/\rho(0)$ on the magnetic field B for c-MWNTs is shown.

The closed circles - c-MWNTs prepared by a usual catalytic method (Kudashov et al., 2002); the open circles - with use of the special procedure (Couteau

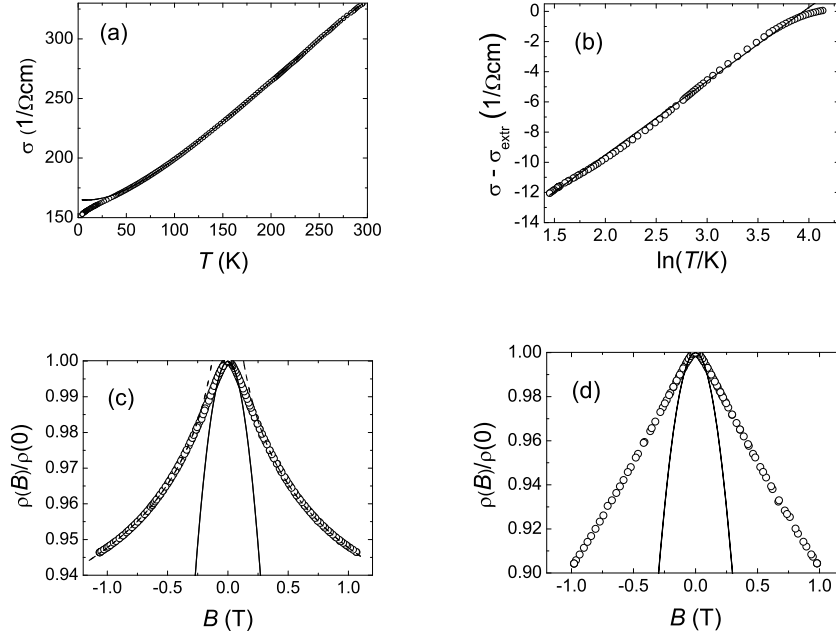


Figure 4. Data for arc-produced MWNTs (a, b, c) and for pyrolytic graphite (d). Temperature dependence of conductivity $\sigma(T)$ (a), anomaly part of conductivity $\Delta\sigma(T) = \sigma(T) - \sigma(T)_{ext}$ (b), and the relative magnetoconductivity $\sigma(B)/\sigma(0)$ from magnetic field B measured at $T = 4.2$ K (c, d). Continuous lines show: $\sigma(T)_{ext}$ receiving by extrapolation of approximation curve from $T \geq 50$ K to $T \leq 50$ K (a); two-dimensional quantum corrections to $\sigma(T)$ (b), asymptotic of quadratic approximation $\sigma(B)/\sigma(0) \approx B^2$ at $B \leq 0.05$ T to B up to 0.3 T (c, d). Dashed lines on (c) show the logarithmic asymptotic $\sigma(B)/\sigma(0) \approx \ln(T)$ from high field to low field.

et al., 2003) which allows to prepare c-MWNTs practically without inclusions of the another form of carbon. Comparing these curves it is possible to see, that in the refined samples in the low magnetic fields (at $B \leq 0.2$ T) the contribution to the negative magnetoconductivity, related to WL, we not observe. $\sigma(B)/\sigma(0)$ for refined c-MWNTs is described by quadratic dependence $\sigma(B)/\sigma(0) \approx B^2$ for all values of field B . $\sigma(B)/\sigma(0)$ for c-MWNT prepared by a usual method are described by quadratic dependence only in low magnetic fields ($B < 0.1$ T). In figure 5(d) the dependence of the relative magnetoconductivity $\sigma(B)/\sigma(0)$ on the magnetic field B is shown for soot. As can be seen from figure 5 the curves for soot and c-MWNTs prepared by a usual catalytic method are very similar at low fields. We suggest that this fact is connected to the presence of impurities of soot in c-MWNTs prepared by a usual catalytic method. Investigation of $\sigma(T)$ of the c-MWNTs shows the presence of quantum corrections $\sigma(T) \approx \ln(T)$ and

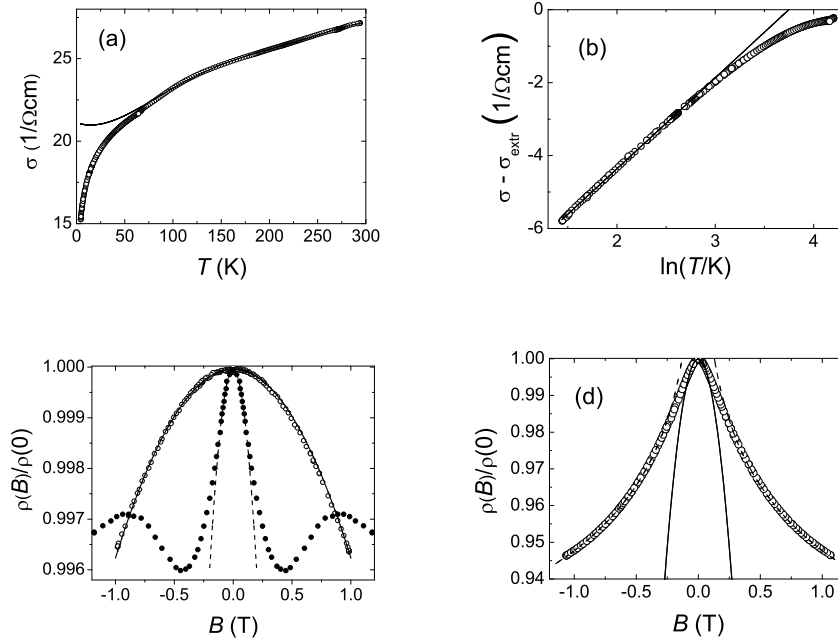


Figure 5. Data for: \circ - catalytic MWNTs without impurities of another forms of carbon (a, b, c); \bullet - MWNTs prepared by a usual catalytic method(c), and Δ - soot (d). Temperature dependence of conductivity $\sigma(T)$ (a), anomaly part of conductivity $\Delta\sigma(T) = \sigma(T) - \sigma(T)_{ext}$ (b), and the relative magnetoconductivity $\sigma(B)/\sigma(0)$ from magnetic field B measured at $T = 4.2$ K (c, d). Continuous lines show: $\sigma(T)_{ext}$ receiving by extrapolation of approximation curve from $T \geq 50$ K to $T \leq 50$ K (a), two-dimensional quantum corrections to $\sigma(T)$ (b), asymptotic of quadratic approximation $\sigma(B)/\sigma(0) \approx B^2$ from $B \leq 0.05$ T to B up to 0.3 T for (curve \bullet on figure c) and soot (d). Dashed line: on (c) - show the quadratic approximation $\sigma(B)/\sigma(0) \approx B^2$, on (d) - show the logarithmic asymptotic $\sigma(B)/\sigma(0) \approx \ln(T)$ from high field to low field.

suggests the two-dimensional character of these corrections (Kawabata, 1980; Lee and Ramakrishnan, 1985; Al'tshuler et al., 1983). The magnitude of the magnetic field which suppresses the temperature correction ($\delta\sigma(4.2 \text{ K})/\sigma(4.2 \text{ K}) \approx 2.7\%$) is estimated as $B \approx 8.5$ T. This corresponds to a quite reasonable magnitude of magnetic length $L_B \approx 60 \text{ \AA}$. Negative magnetoconductivity for IE is also in agreement with the conclusion that $\lambda_c > 0$. However this result has been already obtained from the resistance data.

4. Conclusion

Analysis of the anomalous part of the magnetic susceptibility χ at temperatures below 50 K has allowed us to estimate the electron-electron interaction constant,

λ_c , in the arc-produced MWNTs ($\lambda_c \approx 0.2$) and in graphite ($\lambda_c \approx 0.1$). We found that λ_c does not change in arc-produced MWNTs when the concentration of current carriers is modified by bromination. The analysis of the anomalous part of the conductance and the positive magnetoconductivity demonstrate a dominating contribution of weak localization effects. In pure catalytic MWNTs we found positive magnetoconductivity related only to interaction effects which points to the positive sign of λ_c in these nanotubes. Thus, the analysis of temperature and field dependences of the magnetic susceptibility, conductivity and magnetoconductivity allows us to estimate the electron-electron interaction constant, λ_c , and to determine the effective dimensionality of the current carriers in inhomogeneous systems. On the base of our results we can conclude that the curvature of graphine layers in carbon nanostructures is responsible for the change of constant electron-electron interaction λ_c .

Acknowledgements

The work was supported by Russian Foundation of Basic Research (Grants No: 05-03-32901, 06-02-16005); Russian Ministry of Education and Sciences (Grant ПП.2.1.1.1604); Joint Grant CRDF, and Russian Ministry of Education and Sciences (NO-008-X1).

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